High and Dry: Trading Water Vapor, Fuel and Observing Time for Airborne Infrared Astronmomy

Jeremy Frank
NASA Ames Research Center
Mail Stop N269-3 Moffett Field, CA 94035-1000
Email: frank@email.arc.nasa.gov

Elif Kürklü
QSS Group Inc
NASA Ames Research Center
Mail Stop N269-3 Moffett Field, CA 94035-1000
Email: ekurklu@email.arc.nasa.gov

***Abstract*— Scheduling astronomy observations for the Stratospheric Observatory for Infrared Astronomy (SOFIA) requires assessing tradeoffs between the percentage of scheduled observations, the Line Of Sight Water Vapor (LOS-WV) achieved on those observations, and fuel consumption. This trade space is complex, depending on time of year and specific mixes of observations, and cannot be effectively analyzed by hand. We demonstrate the complexity of these tradeoffs and show that an Automated Flight Planner (AFP) is a crucial part of trade space analysis during flight planning.**

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is NASA's next generation airborne astronomical observatory. The facility consists of a 747-SP modified to accommodate a 2.5 meter telescope. SOFIA is expected to fly an average of 140 science flights per year over its 20 year lifetime, and will commence operations in early 2005. The SOFIA telescope is mounted aft of the wings on the port side of the aircraft and is articulated through a range of 20° to 60° of elevation. A significant problem in future SOFIA operations is that of scheduling Facility Instrument (FI) flights in support of the SOFIA General Investigator (GI) program. GIs are expected to propose small numbers of observations, and many observations must be grouped together to make up single flights. Approximately 70 GI flight per year are expected, with 5-15 observations per flight.

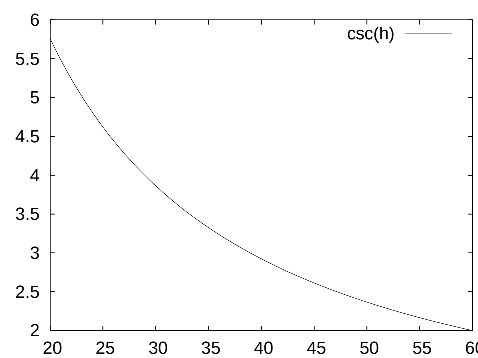

Fig. 1. Variation in $\csc(h)$ in the interval $h = [20°, 60°]$.

An important goal of flight planning for SOFIA is to ensure that line-of-sight water vapor (LOS WV) is minimized during observing [1]. This can be accomplished in one of three ways. It has long been known that water vapor decreases with altitude, thus observing at higher altitude reduces LOS WV. If we analyze $\csc(h)$ where h is the telescope elevation in the range $20° \leq h \leq 60°$ (shown in Figure 1), we see that it takes on values in the range $[2, 5.7]$; thus, choosing the position and time for observing at high telescope elevations reduces LOS WV. Finally, Becklin and Horn [1] showed that, in general, atmospheric water vapor is lower near the poles (as shown in Figure 2); thus, LOS WV can be reduced by repositioning the aircraft.

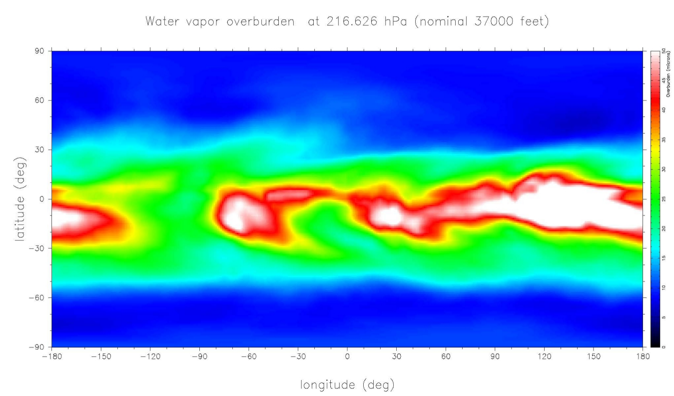

Fig. 2. 5 year average of Water Vapor Overburden at 216.626 hPa (approximately FL 370) over the entire Earth for 31 December. Data provided courtesy of the Wind and temperature data from European Center for Medium Range Weather Forecasting, file provided courtesy of Michael A. K. Gross. For comparison, at 147.474 hPa (approximately FL 450) WV overburden is uniformly below 10μ.

As an airborne observatory, SOFIA allows great flexibility in optimizing any single observation. Judicious choice of takeoff time, altitude selection and observatory position can ensure that LOS WV is minimized for one observation. Unfortunately, there are complex tradeoffs between the takeoff fuel weight, flight duration, percentage of requested observations that can be performed, and average LOS WV for a flight. During flight, aircraft altitude is limited by aircraft weight. The more fuel carried, the longer the flight, but also the more limited the aircraft's initial operating altitude. Fuel is costly (JPA costing \$3.00 a gallon in April of 2005) so using it wisely is important. Furthermore, repositioning the aircraft to seek drier air or maximize telescope elevation will generally require preparatory ”dead-legs” (during which no observations are performed); this will reduce time for observing.

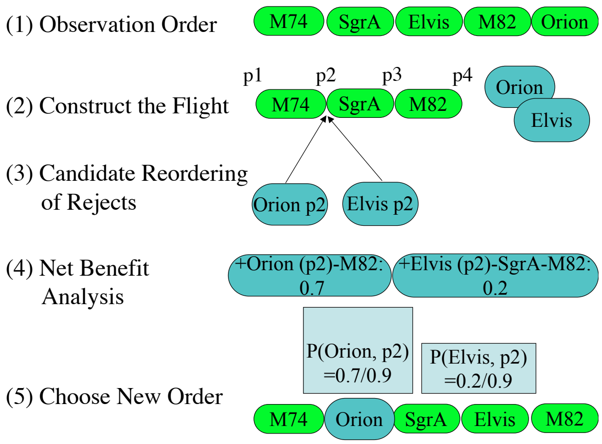

Fig. 3. A schematic view of the inner loop of the Automated Flight Planner. The AFP begins with an ordered list of the observations (1). The Constructor rapidly processes the observations to produce a flight out of a subset of the observations (2). The Critic first determines which observations can be viewed if reordered (3). Net-benefit analysis is then performed (4), and finally some observations are reordered (5) after which the cycle is performed again.

The constraints governing legal flights are complex enough that it is not possible to analyze the tradeoffs up front; one has to generate flight plans and compare them to see the tradeoffs manifested. Furthermore, the tradeoffs cannot be analyzed just once. The trade space will look different for different sets of observations, due to the complex nature of the aircraft’s ground track (for more information see [2]). The trade space will also look different at different times of year; temperature and water vapor change throughout the year, affecting fuel consumption and LOS WV. Finally, the price of fuel is not constant, so operators’ propensity to trade science for operations costs will also change. These tradeoffs are made even more complex because the quantities that are traded are usually incomparable. It is clear that lowering operations costs is valuable, but it is not feasible to put a dollar value on the science output of the entire observatory. Similarly, it is not possible (or at least quite difficult) to determine whether it is worthwhile to sacrifice one observation for lower LOS WV on another observation.

When building schedules for problems such as these, it is often the case that schedule A “dominates” schedule B in the sense that A is more desirable than B by every measure. Thus, a flight A that used less fuel, scheduled the same (or the same number) of observations, and achieved lower LOS WV than a flight B dominates B in this sense. If A does not dominate B, then further care must be taken to decide which one to choose. In the economics literature, this notion of dominance was formalized by V. Pareto, and the set of schedules that do not dominate each-other is called the Pareto Frontier [3].

The SOFIA Automated Flight Planner (AFP) [2] enables rapid exploration of the Pareto Frontier. Figure 3 shows pictorally how the algorithm works. The AFP takes as input a permutation (1) of tasks to schedule. A fast procedure called a

SWO(MaxFlights,MaxRepeats)
\# F is current flight plan
\# B is best flight plan
\# P is a permutation of observations
\# R is rejected observations
\# U is candidate reorderings
for MaxRepeats
  (1) *Generate observation order* P
  for MaxFlights
    (2) Construct the flight
    Construct(P, R, F)
    Update best flight plan B
    if $R = \emptyset$ return F
    else
      (3) *Candidate reordering of rejects*
      for all observations r in R,
      positions p and end times θ after observations in F
        if (Feasible(o, p, θ))
          (4) *Net Benefits analysis of new ordering*
          $C =$ net benefit of starting r at p, θ
          Update U with $< (r, p, \theta), C >$
        end if
      end for
      (5) *Choose new order*
      Form biased probability from U
      Revise order P
    end else
  end for #MaxFlights
end for #MaxRepeats
return B

Fig. 4. Pseudocode of the Automated Flight Planner.

Constructor (2) that treats each observation in order, ultimately scheduling or rejecting them. The permutation and its resulting flight are then analyzed by a *Critic* (3) to construct a new permutation that schedules observations that were previously rejected. Since this might lead to other observations being “pushed out” of the schedule, the AFP estimates the net-benefit “score” (4) of revising the permutation. This score is used to randomly decide how to modify the permutation (5). The cycle is repeated until all tasks are scheduled or for a fixed number of iterations. Figures 4 and 5 are a pseudocode description of the AFP algorithm the reader is referred to [2] for more details. Wind and temperature data from European Center for Medium Range Weather Forecasting (www.ecmwf.int) are used to calculate ground tracks and fuel consumption. We use data from the National Geospatial Intelligence Agency’s Digital Aeronautical Flight Information File to check for Special Use Airspace (SUAs).

We demonstrated the utility of AFP in a study performed on 19 hours of requested observations for three days in December, and 31 hours of requested observations for five days in June; both flights originate and terminate at Moffett Field, CA.

Construct(P, R, F)
Select the takeoff time θ
p is the current position of aircraft in F
#θ is time aircraft at p in F
for observation $o \in P$
    if Feasible(o, p, θ)
        Add p to F
        Update p, θ
      else add p to R
    end for

Feasible(o, p, θ)
o is the observation
p is the current position
D is maximum dead leg duration
(b, d, z) = FindDeadLeg(o, p, θ)
b = heading, d = duration, z = SUA zone
if the dead-leg crosses any SUA zone z
    #Revise dead legs to avoid SUA
    b' is closest heading s.t. all z not crossed
    d' is new duration
    $d = d'; b = b'$
    if $d > D$ **return false**
if observation starts and ends in darkness
    if dead leg home possible following o
      return true
return false

Fig. 5. Subroutines **Construct**(P, R, F) and **Feasible**(o, p, θ) of the Automated Flight Planner.

These observations form an initial "wish list" of science from astronomers interested in using SOFIA, and thus constitute a good test case. Figure 7 shows the Right Ascension and Declination of the requested observations, as well as the total requested time for each observation. Long observations (e.g. 8.7 hours on Sagittarius A W. Arch Filaments in June) were broken up into smaller requests of under two hours each.

The AFP was used to generate the Pareto Frontier for three different fuel loads. These three fuel loads were originally developed in [1] under the assumption of standard atmosphere and used to assess SOFIA's ability to observe in the Northern hemisphere. These fuel loads are described in Figure 6.

Figure 8 and Figure 10 show the percentage of scheduled requests, fuel load and LOS WV of the schedules found by the AFP. We desire flights with low LOS WV and high percentages of scheduled observations. Thus, the Pareto Frontier in this case is the set of schedules in the upper left hand corner of the figures. We see that there are tradeoffs between takeoff fuel load, percentage of requested observations scheduled, and LOS WV. These tradeoffs are prominent in both the December and June flight scenarios. We see "inflection points" where the the number of scheduled observations needed to reduce LOS WV dramatically decreases; these appear to be natural operating points for SOFIA. If operations staff can live with the relatively higher LOS WV, then the choice for SOFIA is to use the Medium fuel load. If the instrument is insensitive to LOS WV and maximizing the science corresponds to maximizing the number of scheduled observations, then using the Heavy fuel load is the best choice. However, for instruments that are very sensitive to LOS WV, the operations staff can choose the Light fuel load.

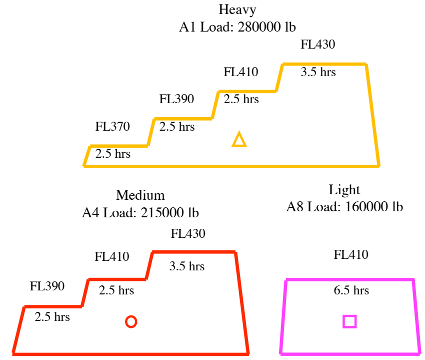

Fig. 6. The 3 fuel loads analyzed in the trade study. The shape of the icon in the middle of the profile denotes the icon used in Figures 8 - 11 to plot the tradeoff between LOS WV and the percentage of scheduled observations.

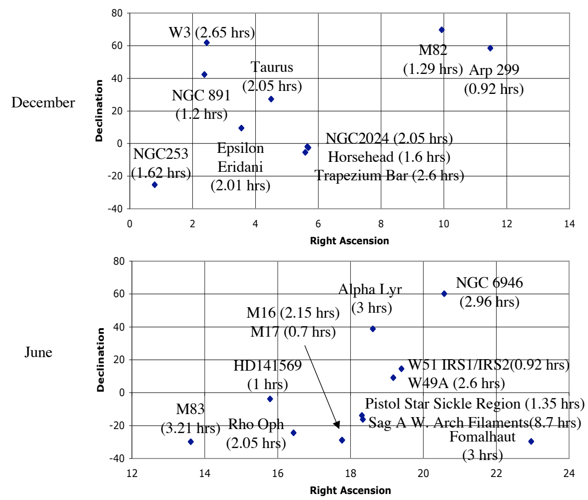

Fig. 7. . The observation requests and observation durations. The top chart shows the Right Ascension and Declinations (coordinates) and requested time for objects to be observed in December, while the bottom chart shows the objects to be observed in June.

The previous graphs showed that adjusting the fuel load leads to a tradeoff between the LOS WV and the percentage of requested observations scheduled. However, as previously stated, the AFP has the ability to reduce LOS WV by increasing the minimum telescope elevation angle. Doing so can have unintended consequences; ensuring that the observations are viewed at the best telescope elevation will generally require longer setup steps, leading to less efficient flights at a minimum, and fewer scheduled observations at worst. Figures 9 and 11 shows the flights in Figures 8 and 10 as well as flights in which the AFP optimizes the telescope elevation

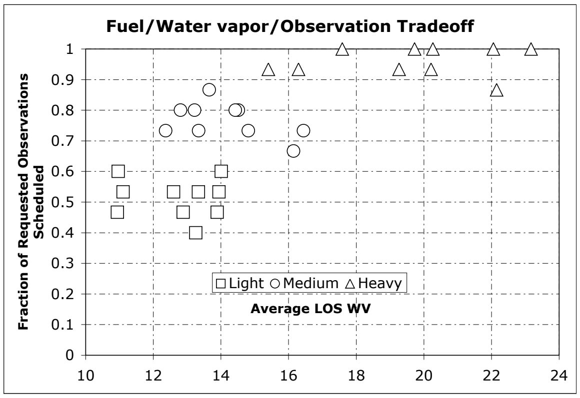

Fig. 8. Tradeoff between takeoff fuel load, LOS WV and fraction of requested observations scheduled for December flight series.

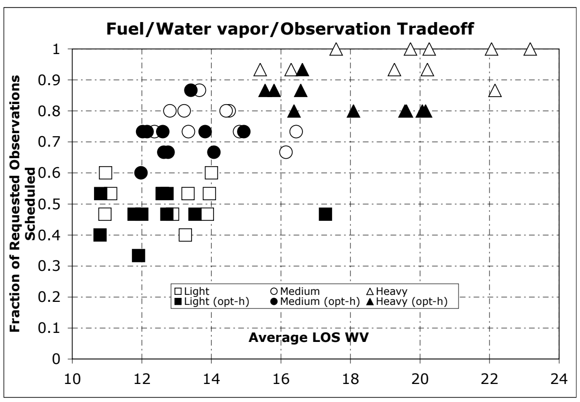

Fig. 9. Tradeoff between takeoff fuel load, LOS WV and fraction of requested observations scheduled for December flight series, including results in which AFP aggressively reduces LOS WV by increasing the telescope elevation angle.

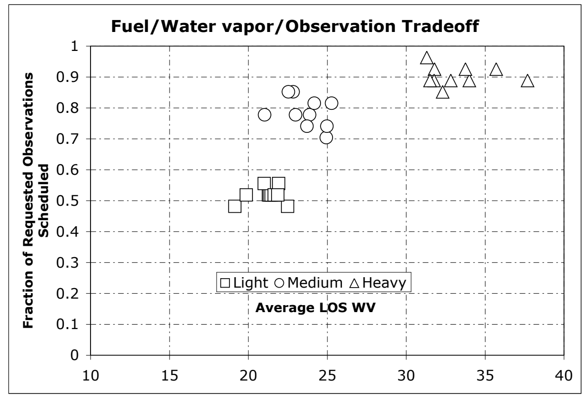

Fig. 10. Tradeoff between takeoff fuel load, LOS WV and fraction of requested observations scheduled for June flight series.

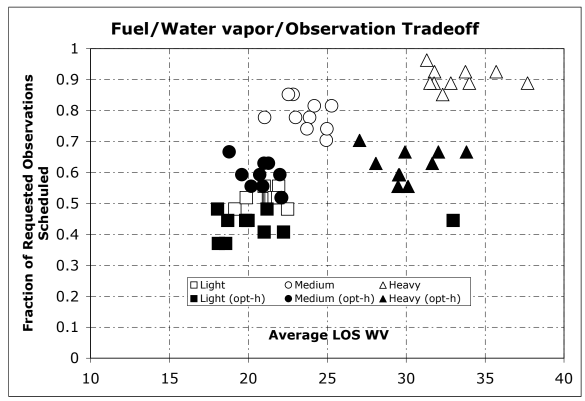

Fig. 11. Tradeoff between takeoff fuel load, LOS WV and fraction of requested observations scheduled for June flight series, including results in which AFP aggressively reduces LOS WV by increasing the telescope elevation angle.

angle to minimize LOS WV (these are plotted with the same fuel load icon, but are dark-filled). The AFP user can select how aggressively to optimize the telescope elevation; in our trade study we used 3 settings, but only present results for the most aggressive setting.

Optimizing the telescope elevation angle does not pay when using the Heavy fuel load for the December or June flight series since generally, as good or better flights are found without optimizing the telescope elevation. Further, for the December flights, optimizing the telescope elevation angle does not qualitatively affect the characteristics of the flights using the Medium or Light fuel loads (Figure 9). By contrast, for the June flights (Figure 11), optimizing the telescope elevation angle can lead to better tradeoffs between LOS WV and the percentage of scheduled requests when the fuel load is Medium or Light. However, the number of scheduled observations is generally quite low when using the Light fuel load (it rarely exceeds 50% and when it does there is usually a better flight using the Medium fuel load).

Flight planning for the previous generation airborne observatory, the Kuiper Airborne Observatory (KAO), was done by hand; annecdotal evidence suggests this required roughly 8 hours to generate one flight plan. When analyzing the December and June flight series used in this paper, the AFP currently generated 600 flight plans in roughly 50 hours of computation time, a feat beyond the capabilities of human flight planners. The rate at which the AFP can generate flights enables humans to assess and analyze complex tradeoffs between fuel, LOS WV and the percentage of scheduled observations. Due to the changing nature of SOFIA scheduling problems, this functionality will play a crucial role in optimizing science and minimizing costs during operations.

References

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[2] J. Frank and E. Kürklü, "Mixed discrete and continuous algorithms for scheduling airborne astronomy observations," in *Proceedings of the* 1^{st} *International Conference on Constraint Programming, Artificial Intelligence and Operations Research*, 2005.

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